Absolute Fluorescence Spectrum and Yield Measurements for a wide range of experimental conditions

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Abstract: The fluorescence yield is the key parameter that allows fluorescence telescope experiments to estimate the air shower energies from the number of UV-fluorescence photons detected. This fluorescence emission is induced by the energy loss in the air medium of the secondary charged particles dominated by the electron/positron component. The fluorescence emission is a line spectrum, of which the line at 337 nm is the strongest. Actual fluorescence telescopes measure the integral of this spectrum in the UV range. The process of photo-deexcitation of the Nitrogen involved in the UV emission is dependent on the pressure, temperature and humidity and requires dedicated measurements at various thermodynamic states of air representative of the atmospheric conditions. Most of the previous experiments have performed measurements on a subset of the dominant spectrum peaks and at standard pressure and temperature conditions with the statistical/systematic errors being at best at the 10% level. For practical fluorescence telescope, these yield measurements have to be extrapolated to account for the whole spectrum and for any atmospheric conditions with poorly known systematic errors. We propose an experiment based on a few MeV electron beam produced by an accelerator, targeting a fiducial volume collecting all the fluorescence light emitted. The goal is to measure the yield absolutely for each spectrum-line and also the integral spectrum by varying the thermodynamic conditions with a statistical accuracy better than 5%. This accuracy can be achieved through control of the electron source intensity, knowledge of primary electron geometrical path and the fiducial volume where the fluorescence light is generated and collected containing more than 95% of the deposited energy and the calibrated detection without relying on any Monte Carlo simulation.

Keywords: Ultra high-energy cosmic rays, air fluorescence technique, JEM-EUSO collaboration

1 Introduction

An extensive air shower is an hadronic shower consisting mostly of an electromagnetic component carrying a very large fraction of the total energy of the shower. This fraction is constant over a wide range of incident energies and this is why the measurement of this electromagnetic component provides a good estimation of the energy of the primary cosmic ray particle. The electromagnetic energy is dissipated by the secondary electrons/positrons from the particle cascade undergoing inelastic collisions loss with the air atoms. This dissipative effect is detectable because the Nitrogen deexcites by UV fluorescence emission into a spectrum including about 30 lines (270 nm-430 nm). Hence, this measurement is a homogeneous calorimetric determination of the shower energy. It is well known that the fluorescence light is proportional to the energy dissipated.

Whereas the global process of energy deposit by charged particles is well known and given by the Bethe-Bloch formula, the details of the effective geometrical energy deposition are not obvious due to the production of secondary delta-rays. A small fraction of them carrying a sizeable fraction of the primary electron energy may deposit their energy at far distances from the electron trajectory. This point raises the critical question of the volume size around the primary trajectory where most of the dissipated energy is contained. An underestimate of the emission volume would lead to an underestimate of the yield due to the energy leakage outside the volume, thus inducing a systematic overestimation of the shower energies.

In a laboratory measurement of the fluorescence yield, scientist controled electron beam replaces favourably the shower electrons (the relationship between the fluorescence yield and the energy loss is well known).

The necessary containment volume is proportional to the logarithm of the energy, and inversely proportional to the pressure. Its exact size for a given pressure, given by the range of the most energetic deltas (electrons) has to be evaluated by a Monte Carlo simulation.

The actual fluorescence telescopes operate by counting the fluorescence photons integrating over the whole UV spectrum ([1], [2], [3], [4], [5]) .

However, the intensity of each emission line varies relatively one to another with the atmospheric conditions ([8], [9], [10]) in a way which is not precisely predictable.

This means one cannot count on the knowledge of a single emission line to predict the behaviour of other lines and naturally that of the integrated spectrum.

Fluorescence telescopes practically measure the total number of photons emitted along a shower track in each of their pixels. From the pixel angular size and the shower distance one can calculate the shower-track-length. Defining the linear fluorescence yield as the ratio of the number of photons per unit length, one can then estimate the number of electrons crossing the field of view of the pixel.

From the number of electrons, one deduces the dissipated energy of the shower according to the Bethe-Bloch formula.

The essential factor for a precise absolute energy measurement of the shower is the fluorescence yield.

2 Status of the Previous Measurements

Up to now, there have been two kinds of experiments: 1) those with radioactive sources, simple table-top experiments, hence the first ones, but not very precise (about 15 % per line, due to low counting rate); 2) beam experiments, more complex but giving more precise results. The main one is the AirFly project ([6]), which measured the properties of the most intense line (337 nm) in all atmospheric conditions. They also measured the different line yields relative to the 337nm line, but at one pressure value only (1 atm). If their precision on the 337 nm line is good (4%), the extrapolation to the integral spectrum at any atmospheric condition needs to be improved.

For all the reasons mentioned above, we propose an experiment where we will measure the properties of each individual line in all atmospheric conditions using an experimental setup common to all lines at the same time.

3 Fluorescence Yield measurement issues

3.1 Control of the volume where energy deposit and light emission occurs

The goal is to collect the fluorescence light emitted anywhere in the target volume, independently of the location of the emission. This requires to use an integrating sphere. The fraction of the light detected on a port on the surface of the sphere is proportional to the ratio of the area of this port to the total inner surface of the sphere. The size of this sphere can be estimated at the lowest pressure : 0.1 atm corresponding to an altitude of 10 km. This corresponds to a radius of 20 cm for a 85% energy containment for an electron energy of 4 MeV [8]. At 1 atm, for the same radius, the contained energy is 91%, i.e. very close to the 0.1 atm value. This is due to the fact that only a very small numbers of deltas have energies such large that their ranges exceed the sphere radius. This is an acceptable compromise between the total energy containment and the size of this sphere. This missing energy will be treated in section 6.1.

3.2 Temperature, pressure, humidity dependence

The effective atmospheric conditions range from 1 atm to 0.1 atm in pressure, from 20°C to -60°C and the humidity varies from saturation to 1% of the saturation level. Each fluorescence line is affected differently by these parameters. The weighted sum of the yield measurements of individual lines must be checked by a specific integrated measurement through a PMT equipped with a BG3 filter identical to the one used in Telescope Array and JEM-EUSO. The Pierre Auger Observatory uses a similar filter.

4 Experimental Set-Up

The scheme in figure 1 explains the experimental setup proposed for the yields measurements. The electron beam arrives from the left, goes inside the sphere, being diffused by multiple scattering and exits the sphere towards a precise Faraday cup under vacuum. This beam is bunched at 5 Hz. Each bunch has a time length of 8 ps and a total charge of 100 pC (PHIL accelerator [12], [13]) . The energy will be 3-5 MeV with a maximum transverse size of 1mm (sigma), to be reduced in the future. The PMT1, equipped with a BG3 filter is used to monitor the emitted light. This tube has been calibrated before and with a 2% accuracy. It then becomes a NIST PMT.

A small fraction of the fluorescence light is collected by an optical cable made of 61 silica step-index fibers of 0.1 mm diameter. Four of these are used to measure accurately the integrated light with the PMT2 also equipped with the BG3 filter. 57 fibers, arranged vertically as a monofiber layer of 5.7 mm height and 0.1 mm thickness, enter a grating spectrometer (the grating being naturally vertical). The entrance slit of this spectrometer allows to restrict the angular distribution of the light at the fiber exit. Choosing a slit width of 0.1mm provides a resolution of 0.1 nm. The grating has 600 grooves per mm to cover 100 nm. The light is collected on a CCD (1024 horizontal pixels, along wavelength axis and 256 vertical pixels parallel to the slit), which is LN2 cooled to achieve a background noise of 1 electron per pixel per hour. The whole wavelength range from 300 nm to 400 nm is measured only once. Even if the PMT are not the same for the experiments and this measurement, the response of the photocathode is well known and taken into account (weighted with respect to the lines strenghts). All used PMTs have been calibrated (see section 6).

Notice that a movable mirror located after the grating can direct the light toward an external output slit. This output light is detected by the PMT3, which will be used for the calibration of the CCD.

4.1 Temperature and Humidity effects

In order to study effects of temperatures down to -60°, a Dewar will be set around the sphere. Care will be taken to protect all the ports in this Dewar from freezing. Humidity will be set by introducing known partial pressure of water vapour, according to the pressure and temperature conditions.

5 Measurement

The goal of the measurement is to determine precisely the relative shape of the fluorescence spectrum such that the statistical accuracy of the contribution of each line is better than 1%. This measurement is carried out by the CCD. It requires to have detected at least 10^4 photons on the lowest intensity emission line. But the CCD is not a photo-detector representative of the actual measurement in fluorescence telescope. At the same time, the integral spectrum is recorded in the calibrated PMT2, similar to those used in Telescopes. In this way, we can relate the whole spectrum of the CCD measurement to the PMT photon units. Then, the calibration procedure will establish the relation between this PMT photon units to the amount of photons emitted inside the sphere. Notice, the number of primary electrons is given by a Faraday cup acting as a beam dump.

The PMT1 monitors the number of photons inside the sphere to get a first estimate on the ratio of the number of photons in the sphere to the number of photons to the PMT2.

6 Calibration

The scheme in figure 2 gives the calibration procedure. The purpose of the calibration is to estimate in a more precise and absolute way the light ratio between the total light generated in the sphere to the light detected in the CCD or reaching the PMT2. To mimic the beam geometry, the light source will be a 1 mm scintillating fiber illuminated from outside the sphere by a UV LED. The light is monochromatic within 10 nm.

All the PMTs are calibrated in gain and their efficiency is absolutely determined at 2 % level by a patented method developped by Lefeuvre et al [7], [14]. This method is based on the comparison between the PMT and a NIST-photodiode precise to 1.5 % [15]. The variation of the ratio of photoelectrons produced in the PMT to the photons hitting this tube (in units of Ampere per Watt) is known. With this method, the PMT becomes a "NIST-PMT". This calibration method is precise because it is made in single photoelectron mode where gain and efficiency are totally de-correlated.

The PMT3 is calibrated with the same accuracy, the mirror (reflectivity 99%) inside the spectrometer is tilted such that the light from the grating goes through a slit of the same width than one horizontal pixel of the CCD. Scanning the emission wavelength profile of the scintillating fiber, we can compare the signal units of the CCD to the signal units of the PMT3. The attenuation of the number of photons from the sphere to the grating induced by reflection on interface, numerical aperture, fibers transmission is similar for the fluorescence yield measurement and the instrument calibration. Their contributions are then compensated by the measurement of the calibration ratio.

6.1 High pressure

We saw that 15% energy is missing at 0.1 atm and 9% at 1 atm. In the yield measurement the remaining uncertainty will be the fraction of high energy deltas escaping the sphere. This contributes to the order of 5% with an error of 10% on the energy leaked out. For a 4 MeV beam, the highest energy delta is 2 MeV with a range of around 8 m at 1 atm. It is impracticable to make a sphere and a Dewar that big. We plan to get around this problem by increasing the pressure and maybe decreasing the beam energy until all the deltas are stopped in the 20 cm sphere. Then a direct comparison of the energy loss with the Bethe -Bloch formula will provide the correction for the escaped energy.

7 Conclusion

Up to now the fluorescence yield of the brightest line at 337 nm has been measured in an absolute way in one set of conditions, whereas fluorescence yields at the other wavelengths have been relatively measured for different conditions.

This experiment will provide both the integrated measurement and fluorescence yields for each line with high accuracy better than 5% other a wide range of atmospheric conditions.

An current set-up with a small integrating sphere (6 cm diameter) is tested at PHIL accelerator in order to valid the whole system.

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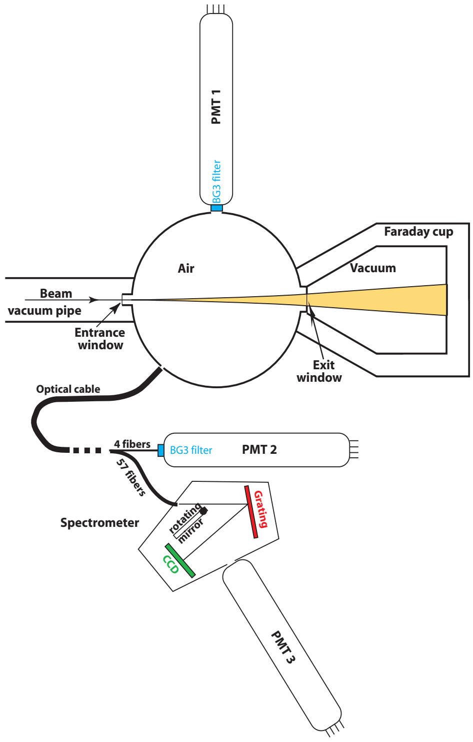

Figure 1: Design of experiment.

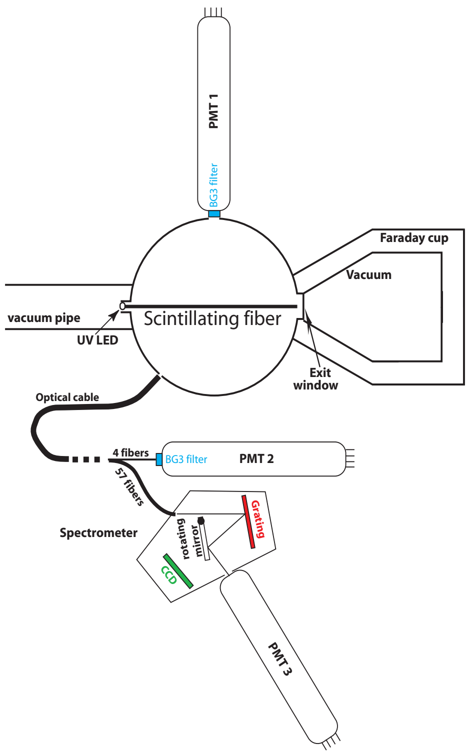

Figure 2: Calibration of the experiment.